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Stochastic Convective-Dispersive Transport Model for Wastes Disposed at the 106-Mile Ocean Disposal Site

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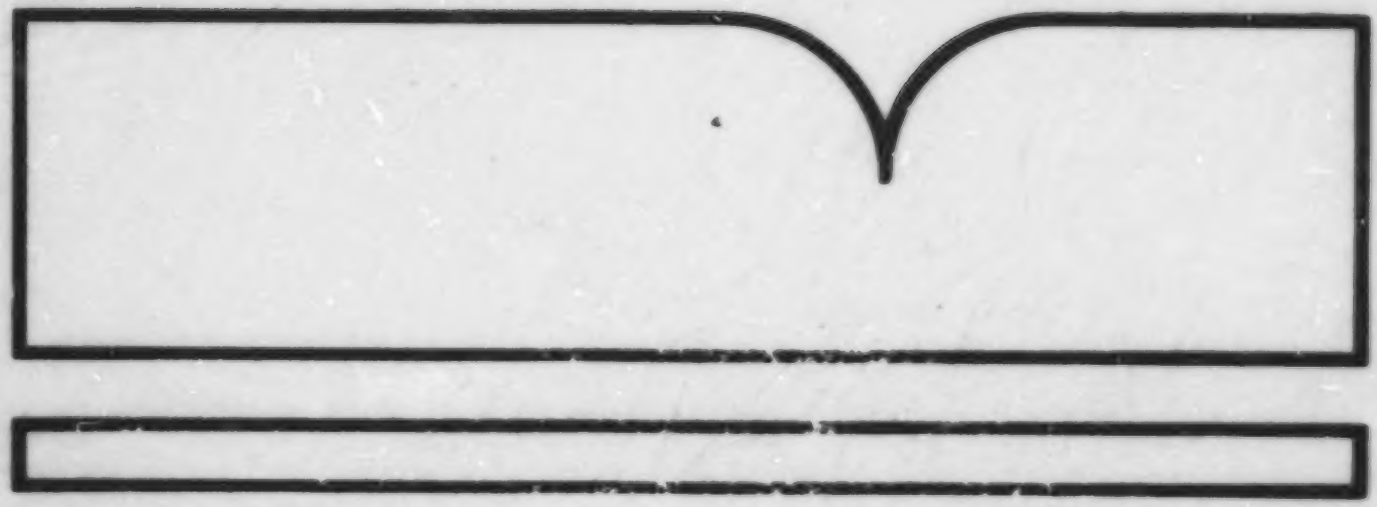

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A STOCHASTIC CONVECTIVE-DISPERSIVE TRANSPORT MODEL FOR WASTES DISPOSED AT THE 106-MILE OCEAN DISPOSAL SITE

by

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A two-dimensional, stochastic, convective-dispersive transport model was developed to predict expected dilutions for wastes disposed at the 106-Mile Ocean Disposal Site. The major model assumptions were: 1) wastes were completely mixed vertically and remained in the upper mixed layer, 2) the expected center of mass of a discrete dump of material was transported from the disposal site with the mean horizontal current, 3) expected dispersion of a discrete dump of material about its center of mass was determined by the variance and correlation structure of current velocities, and 4) the expected plume from a series of dumps over a period of time can be estimated by superimposing the expected distributions of the individual dumps.

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A Stochastic Convective-Dispersive Transport Model for Wastes Disposed at the 106-Mile Ocean Disposal Site

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ABSTRACT

A two-dimensional, stochastic, convective-dispersive transport model was developed to predict expected dilutions for wastes disposed at the 106-Mile Ocean Disposal Site. The major model assumptions were: 1) wastes were completely mixed vertically and remained in the upper mixed layer, 2) the expected center of mass of a discrete dump of material was transported from the disposal site with the mean horizontal current, 3) expected dispersion of a discrete dump of material about its center of mass was determined by the variance and correlation structure of current velocities, and 4) the expected plume from a series of dumps over a period of time can be estimated by superimposing the expected distributions of the individual dumps.

Satellite thermal imagery and expendable bathythermograph (XBT) profiles of temperature in the winter indicated a distinct shelf water / slope water front extending from the surface to the shelf break at the 80 meter isobar. In the summer, satellite thermal imagery and XBT profiles indicated that the shelf water / slope water front was less distinct in the surface layer above the seasonal thermocline, but persisted below the seasonal thermocline.

The shelf water / slope water front was treated in the model in two ways: as a transparent boundary or as a reflecting boundary. A transparent boundary is more appropriate for summer conditions above the seasonal thermocline. A reflecting boundary is more appropriate for winter simulations. The Gulf Stream was modeled as an absorbing boundary. The permanent pycnocline at 100 meters can be used to define the bottom of the upper mixed layer for the model in the winter. The seasonal thermocline, which reaches its shallowest depth of approximately 20 meters in the late summer, can be used to define the bottom of the mixed layer for summer simulations.

1. INTRODUCTION

The 106-Mile Ocean Disposal Site is located just beyond the seaward limit of the continental shelf of the northeast United States (200-meter isobath), and is in water of depths varying between 1700 and 2750 meters within the disposal site boundaries (between latitude 38°40' and 39°00'N and longitude 72°00 and 72° 30'W). The site has been designated for disposal of sewage sludge on a five year interim basis by the U.S. Environmental Protection Agency (U.S. Federal Register, 1984a). The designation was based on the site's dispersive characteristics, its remoteness from recreational areas, and its location seaward of the abundant and valued living resources of the continental shelf (O'Connor et al., submitted). The only other active sewage sludge disposal site in that region is located in New York Bight, 12 nautical miles seaward of New York harbor, and EPA has indicated its intentions to remove that site's designation status for sewage sludge (U.S. Federal Register, 1984b). If sewage sludge that is currently disposed in the New York Bight were transported to the 106-Mile Site, the annual amount of sludge that would be disposed at the 106-Mile Site could exceed 7.6 millions tons. This possibility serves to focus attention on the need to develop methods for assessing the probable transport and fate of wastes disposed at this deep ocean site.

The 106-Mile Site is normally occupied by slope water, and is bounded on the west by a quasi-stable shelf water / slope water front, and on the south and east by the edge of the Gulf Stream (Fig. 1). Exchange processes at these fronts are of particular interest, since they will determine the extent that waste material disposed at the 106-Mile Site may be mixed into the relatively productive shelf water region, or may be entrained into the Gulf Stream and eventually dispersed into the North Atlantic. Because the positions of these major fronts are not static, the 106-Mile Site can be occupied occasionally by shelf water or by Gulf Stream waters. In addition, large Gulf Stream warm-core rings, which are eddies that form as Gulf Steam meanders pinch off from the stream and trap parcels of Sargasso Sea Water, can pass through the disposal site. These eddies, which typically have diameters of 100 km, can affect circulation at the disposal site for periods up to three weeks (Bisagni, 1976).

The purpose of this paper is to describe a stochastic convective-dispersive transport model for wastes disposed at the 106-Mile Site which accounts for the possibility that waste constituents may not be mixed into shelf water because of the barrier presented by the shelf water / slope water front. Data sources such as hydrographic sections and satellite-derived sea

surface temperature (SST) maps are used to define the strength and position of this front. The model represents an extension of the work by Paul et al. (in press), who described a preliminary framework for calculating bounds on time-averaged concentration fields for selected sewage sludge constituents that could result from anticipated sewage sludge disposal at the 106-Mile Site.

2. THE SHELF WATER / SLOPE WATER FRONT.

Cross-frontal exchanges of momentum, heat, salt, organic and inorganic materials is known to occur at the shelf / slope front; however, the detailed mechanisms by which these exchanges occur are not well understood (Bowman and Esaias, 1977). In this section, descriptive information concerning seasonal changes in the shelf / slope front is presented which provides a rationale for treating the shelf / slope front as either a transparent boundary or a reflective boundary in the contaminant distribution model.

A primary characteristic of the shelf water / slope water front between Cape Cod and Cape Hatteras is that it seems to straddle the shelf break, the zone of abrupt increase in bottom slope marking the transition between the continental shelf and upper continental slope (Bowman and Esaias, 1977). This front, first described by Bigelow (1933) and Bigelow and Sears (1935), is particularly sharp and has a simple structure during the winter months of November through March. During this time, the shelf water is fairly well-mixed vertically, with temperatures and salinities increasing from 4°C and 32.5 °/oo near the shore to about 8°C and 33.5 °/oo just shoreward of the front (Bowman and Esaias, 1977).

A typical winter hydrographic section taken from the Oleander, a ship of opportunity which originates near the mouth of New York harbor and crosses the northeast corner of the 106-Mile Site, illustrates major frontal features (Fig. 2). Across the front, temperature, salinity, and density increase by about 5°C, 2 °/oo, and 0.5 sigma-t units, respectively. A satellite image obtained May 5, 1983 illustrates that the slope water region is bounded to the north and east by the relatively cool shelf water, displayed in blue, and is bounded on the south and west by the Gulf Stream, displayed in yellow (Fig. 3). It is also evident that the 106-Mile Site was occupied by a warm-core Gulf Stream ring at this time.

Because relatively sharp temperature and salinity discontunities occur during the winter at the shelf / slope front, and because the front is a surface to bottom feature (Fig. 2), it is reasonable to model the winter shelf / slope front as a reflective boundary. This type of boundary would inhibit mixing of contaminants from slope water onto the shelf.

In the summer, the progressive development of the seasonal thermocline causes the surface manifestation of the shelf water / slope water front to become less distinct. Because of the typical spatial sampling interval on hydrographic surveys, a surface temperature front is often not detected during the summer. However, because of the finer spatial resolution

obtained routinely by satellites (nominally 1 km for the NOAA - 7 satellite used in this study) the relatively weak shelf / slope front can be detected by satellite infrared imagery for much of the summer. The sharp density front observed in the winter gradually disappears in the surface layer during the summer. However, intrusions or upwelling of relatively cool dense water at the shelf break occasionally interrupt this trend. By the end of the summer, surface layer temperature, salinity, and density increase in a smooth fashion from the coast toward the warmer, more saline conditions of the Sargasso Sea. A hydrographic section sampled at the end of the summer (Fig. 4) indicates the presence of a weak shelf water / slope water density front below the surface thermocline between stations 20 and 24. However, the corresponding sea surface temperature map illustrates the absence of a distinct shelf / slope front in the upper layer (Fig. 5). A warm-core Gulf Stream ring is evident north of the hydrographic section line and west of the 106-Mile Site in the slope water region.

Because the shelf / slope front is relatively weak in the upper mixed layer during the summer, more mixing across the front may occur than during the winter. For summer conditions, it is reasonable to model the shelf / slope front in the upper mixed layer as a transparent boundary. Wastes in the slope water could mix onto the shelf with this type of boundary.

3. EXTENSIONS TO THE STOCHASTIC CONTAMINANT DISTRIBUTION MODEL.

Detailed a priori predictions of the transport and fate of individual dumps of sewage sludge are not possible because physical oceanographic conditions can be quite variable in the vicinity of the 106-Mile Site. A model proposed by Paul et al. (in press) represented a preliminary framework for calculating bounds on the time-averaged concentration fields for selected sewage sludge constituents that could result from anticipated sewage sludge disposal at the 106-Mile Site. Both the Paul et al. (in press) model, and the model described in this paper are based on a number of simplifying assumptions. These include: 1) no explicit distinction between dissolved and particulate phases of contaminants; 2) contaminants are transported with the water motion in the upper mixed layer; 3) no vertical loss of contaminants associated with gravitational settling out of the upper mixed layer; and 4) contaminants are conservative, i.e. they do not decay. A consequence of these assumptions is that, at a given point in space, wastes are completely mixed vertically in the upper mixed layer. Thus model results can be interpreted as limiting cases of the dilution or concentration fields that may result if all contaminants resulting from anticipated disposal of sewage sludge are dissolved in upper mixed layer of the ocean.

Modeling physical transport requires spatial and temporal averaging in order to characterize some form of mean advective flow and diffusion. For the purpose of this paper, we will consider only the long-shelf and cross-shelf components of the currents. Information necessary to estimate the oceanographic parameters has been based on an analysis of long-term current meter mooring records. Unfortunately, no such current meter records are available for the 106-Mile Site. It was necessary to utilize measured currents at the Woods Hole Oceanographic Institution (WHOI) Site D (Fig. 1) to derive these model parameters. WHOI Site D is approximately 200 km east-northeast of the 106-Mile Site in a similar bathymetric regime, except that the long-shelf orientation of the shelf break is approximately westward at Site D and is approximately south-westard at the 106-Mile Site. In order to estimate the mean current flow at the 106-Mile Site, it was assumed that the average westerly currents at Site D would continue to follow the bathymetry into and beyond the vicinity of the 106-Mile Site. This assumption was consistent with an assessment of the general physical oceanography of the 106-Mile Site made by Ingham et al. (1977). In particular, Paul et al. (in press) applied a 65° rotation to the Site D currents to represents the effect of the change in bathymetric orientation on mean flow between Site D and Cape Hatteras. Because of the emphasis on the shelf water / slope water boundary in this paper, the modeled relationship between bathymetry and mean flow has been refined. Instead of

using a 65° rotation, the Site D current data has been rotated by 50° to account for the change in orientation of the shelf between 40°N and 37°N latitude. An additional 40°rotation was then applied in the range of 37°N to 35°N latitude to account for the change in the shelf break orientation in the Cape Hatteras region.

In order to statistically characterize deviations in currents about long-term mean values, the probability distributions, power spectra and cross spectra of the current meter data from WHOI Site D have been determined for the two horizontal components of the currents. The probability distributions for both the cross-shelf and long-shelf components of the current have been found to be approximately Gaussian (Paul et al., submitted). Corrsin, (1961) notes that this Gaussian character of velocity is often observed in turbulent flow,[1] and may be simply the result of something like a "central limit theorm",[2] in the sense that non-linear dynamic effects influence the acceleration directly, whereas the velocity is the integral (sum) of accelerations.

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[1] Experiment has shown the surprising fact that probability densities of velocities in grid turbulence are Gaussian within the limits of accuracy (Batchelor, 1953).

[2] One form of the central limit theorm simply states that very large sums of small random events tend to become Gaussian, under certain restrictions, even when the individual elements are not Gaussian.

Because of the underlying Gaussian character of velocity fluctuations, a dispersing plume of waste material can be characterized as a dispersing Gaussian cloud which is advected downstream due to the mean flow, and which increases in size as a consequence of turbulent dispersion. The cloud size can be described by the long-shelf (σ_l^2) and cross-shelf (σ_c^2) variance in waste constituent concentration about the cloud's center of mass. Taylor's hypothesis for relating point measurements in time to fixed-time measurements over space (Taylor, 1921), can be used to derive an approximation for the growth in cloud size as a function of time (Csanady, 1973; Paul et al., in press). During an initial period, σ_l^2 and σ_c^2 vary as a function of time squared. This has been found to be a good approximation for the initial, rapid plume growth rates observed in dye studies and is the form of cloud growth assumed by Paul et al. (in press). In a later, slow growth phase, σ_l^2 and σ_c^2 vary linearly with time. From a statistical standpoint, the latter slow growth phase can be considered to be a "random walk" process. Paul et al. (submitted) consider both the rapid and slow growth phases of cloud growth and obtained revised estimates of contaminant distributibn. In this composite plume growth rate model, the shift from the rapid to slow growth phase corresponds to the estimated Lagrangian decorrelation time scale of 10 days in the along-shelf direction, and 5 days in the cross-shelf direction.

In addition to specification of a functional form for the growth in cloud size as a function of time since release, it is necessary to specify the absolute levels of σ_l^2 and σ_c^2. A high mixing case was simulated by Paul et al. (in press) by using the actual variances in the current meter records measured at WHOI Site-D as estimates of σ_l^2 and σ_c^2. For a low mixing case, Paul et al. (in press) reduced the measured WHOI Site D current meter variances by two orders of magnitude to represent a hypothetical quiescent period that did not involve storm-induced mixing. This corresponds with the initial dilutions that have been observed at the 106-Mile Site prior to the passage of storms (O'Connor et al., 1983). However, Paul et al. (submitted) note that using the actual variances in the current meter records (the high mixing case) may lead to an overestimate of dispersion, since the current meter record contains rotational energy at inertial and tidal frequencies that does not lead to dispersion on the large spatial scales of interest. A low pass filter was designed to remove energy in the current meter records with periods less than one day and to obtain revised estimates of σ_l^2 and σ_c^2. For the WHOI Site D current meter record used by Paul et al. (in press),[3] this procedure resulted in reducing measured current meter variances by 40%. Storm

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[3] WHOI Site D (39 9.7' N, 69 57.1' W) at 54 meters for 12/12/71 to 3/5/72 (Tarbell and Whitlatch 1977).

induced mixing is included in the filtered current meter record. Model simulations based on the low pass filtered data will be refered to as an intermediate mixing case. Parameter values used to model low and intermediate mixing cases are included in Table 1.

In the extended model presented here, the shelf water / slope water front is treated in two possible ways: as a transparent boundary, or as reflective boundary. A transparent boundary implies that the shelf / slope front does not inhibit mixing of contaminants from the slope onto the shelf. If the concern is possible impact of contaminants on the relatively productive living resources on the shelf, a transparent boundary condition represents a potential worst case situation. This may be an appropriate assumption for summer when there are small and relatively smooth density, temperature, and salinity gradients between the shelf water and slope water in the upper mixed layer. A reflective shelf /slope front may be an appropriate approximation for winter simulations on the basis of the relatively sharp gradients that occur across the shelf / slope front over the entire water column during this period. Spring and fall conditions represent transitional periods in which the shelf / slope front can still be distinct to varying degrees.

Table 1. Velocity characteristics used for stochastic convective-dispersive model calculations

		Intermediate mixing[1]		Low mixing[2]	
Mean vector	east	-12.34		-12.34	
(cm/sec)	north	1.12		1.12	
Variance-covariance	E	E-N	89.90 16.90	2.50	-0.50
matrix	E-N	E	16.90 92.64	-0.50	2.57
$((cm/sec)^2)$					
Coefficient of	east	0.77		0.13	
variation	north	8.59		1.43	

[1] Based on observed values at Site D (39°9.7' N, 69°57.1' W) at 54 meters for 12/12/71 to 3/5/72 (Tarbell and Whitlatch 1977), that have been low pass filtered to remove inertial and tidal motion (40% of the variance filtered out).

[2] Based on same observed values at Site D, but with a coefficient of variation that has been reduced by a factor of ten.

The stochastic convective-dispersive model used in this paper is based on the same assumptions used by Paul et al. (in press), with three exceptions: 1) the shelf water / slope water boundary condition, 2) the relationship used to model the affect of bathymetry on the mean flow, and 3) the use of the composite plume growth rate model proposed by Paul et al. (submitted) for some of the calculations. All dilution results discussed in this paper have been based on an assumed upper mixed layer depth of 100 meters, and have been based on dispersion related to the same current meter records measured at a 54 meter depth at WHOI Site D used by Paul et al. (in press, submitted). An initial estimate for dilutions that may occur during the summer above a 20 meter seasonal thermocline, would be obtained by reducing the dilutions described in this paper by an additional 80%.

4. MODEL RESULTS

As discussed above, the stochastic convective-dispersive model can be implemented in the following modes: 1) specification of the absolute levels for σ_l^2 and σ_c^2 (low, or intermediate mixing), 2) plume growth rate (time-squared growth, or composite plume growth rate with initial time-squared growth followed by linear growth, and 3) shelf water / slope water boundary condition (transparent or reflective condition). For presentation here, three cases are discussed: 1) low mixing with rapid plume growth, 2) intermediate mixing with rapid plume growth, and 3) intermediate mixing with the composite plume growth. All three cases are run with the two different shelf water / slope water boundary conditions. Results are illustrated in terms of long-term average dilution contours which have been normalized to an initial unit concentration. The average concentration contours for individual contaminants can be estimated by multiplying the dilution factors by the actual initial concentrations in sewage sludge. In addition to presenting dilution contours, dilutions are plotted as a function of distance (km) downstream of the 106-Mile Site along the mean flow line and along the shelf / slope front. The model results do not include the additional dilution that would occur when wastes are entrained into the Gulf Stream. This would occur at a point approximately 400 km downstream along the shelf break, and on average would occur at a point approximately 350 km downstream along the mean flow line.

Case 1: Low Mixing - Rapid Plume Growth Rate

The dilution contours based on simulations with and without the reflective shelf water / slope water boundary are presented in Fig. 6 and 7 respectively. With a transparent shelf / slope boundary, it is apparent that some sludge constituents may be mixed into the shelf water south of 38 north latitude; however average dilutions relative to initial concentration in sludge would still be greater than $1 * 10^7$. The presence of a reflective boundary at the shelf / slope front prevents sludge constituents from reaching the slope water region. However, because the fraction of total contaminant mass that reaches the shelf / slope boundary is relatively small, a reflective boundary condition only results in a marginal reduction in dilution along the shelf / slope front at distances greater than 100 km from the 106-Mile Site (Fig. 9), and has no effect on dilutions along mean flow line (Fig. 8). At a point 350 km from the 106-Mile Site along the shelf, the reflective boundary leads to a reduction in dilution by 25%, (Fig. 9).

Case 2: Intermediate Mixing - Rapid Plume Growth Rate

The dilution contours for the transparent and reflective boundary simulations (Figs. 10 and 11, respectively) indicate

that dilutions do not change within 100 km of the the 106-Mile Site as a consequence of the reflective boundary. When a transparent boundary is simulated, sludge constituents may be transported onto the shelf, but, as in the low mixing case, dilutions greater than $1 * 10^7$ are predicted. The presence of a reflective shelf / slope boundary prevents sludge constituents from reaching the shelf water region, and has the effect of reducing average dilutions in the slope water region greater than 100 km downstream of the 106-Mile Site (Figs. 12 and 13). At points 350 km from the 106-Mile Site, dilutions are reduced by 40% and 50% along the mean flow line and shelf boundary, respectively.

Case 3: Intermediate Mixing - Composite Plume Growth

In the initial phase of dispersion, the composite plume growth model includes the rapid (time-squared) growth of σ_1^2 and σ_c^2 used in Case 2. Thus modeled dilutions near the 106-Mile Site are similar in Cases 2 and 3 (Figs. 10 and 14). However, after an initial rapid plume growth phase, the composite plume growth model uses growth rates for σ_1^2 and σ_c^2 that vary linearly with time, and the results differ from those in Case 2.

Once again, when the shelf / slope front is modeled with a transparent boundary it is apparent that sewage sludge constituents may be mixed onto the shelf, but once again with average dilutions greater than $1 * 10^7$ (Figs. 14 and 17). As in the low mixing case, the presence or absence of a reflective shelf / slope front does not affect dilutions along the mean flow line (Fig. 16). The presence of a reflective boundary results in less dilution along the shelf / slope front, leading to a reduction in dilution by approximately 40% at a point 350 km along the shelf / slope front (Fig. 17). As in Case 1 and Case 2, a convergence in the average dilution along the mean flow line and along the shelf / slope front occurs when the front is modeled as a reflective boundary.

6. SUMMARY

The model results presented in this paper are intended to represent two extreme cases: 1) the possibility that sewage sludge constituents would be mixed onto the shelf across the shelf / slope front, and 2) the possibility that the presence of the shelf / slope front would inhibit the mixing of waste constituents onto the shelf. A transparent boundary is used to model the former case, and may be appropriate during the summer when the shelf / slope front is relatively weak. A reflective shelf / slope boundary is used for the latter case and is appropriate during the winter when the shelf / slope front is relatively sharp. The average position and strength of the shelf / slope frontal boundary has been determined from synoptic sea surface temperature maps based on data collected by the NOAA-7 satellite, and from hydrographic (XBT) sections obtained by ship. The Gulf Stream is usually located 350 to 400 km downstream of the 106-Mile Site, and is assumed to be the major sink for wastes transported in the upper mixed layer.

The stochastic convective-dispersive model was implemented for three cases: 1) low mixing, with rapid plume growth rate, 2) intermediate mixing, with rapid plume growth rate, and 3) intermediate mixing, with composite plume growth. For all the results presented, some mixing of sewage sludge onto the shelf occurs when the shelf / slope front is modeled as a transparent

boundary. For those shelf water areas that may be impacted by proposed sewage sludge disposal, the model results suggest that average dilutions relative to concentrations in sewage sludge would be greater than $1 * 10^7$. A reflective boundary prevents sewage sludge constituents from reaching the shelf water region, but does not affect average dilutions within 100 km downstream of the 106-Mile Site.

The greatest differences between the three cases occurs at points greater than 200 km downstream from the 106-Mile Site. The presence of a reflective boundary had the least effect on the low mixing case, with no reduction in dilution along the mean flow line, and only a 10% reduction in dilution at a point 200 km along the shelf / slope front. For the intermediate mixing case with composite plume growth, the presence of the reflective shelf / slope boundary did not affect dilutions along the mean flow line, but resulted in a 35% reduction in dilution at a point 200 km along the shelf / slope front. The reflective boundary condition had the greatest effect on the intermediate mixing case with rapid plume growth. In this case the reflective boundary resulted in 30% and 35% reductions in average dilutions at points 200 km along the mean flow line, and along the shelf / slope front, respectively. For all three cases, the presence of a reflective boundary results in a 30% - 40% reduction in the average dilution 350 km downstream of the 106-Mile Site along the shelf / slope front.

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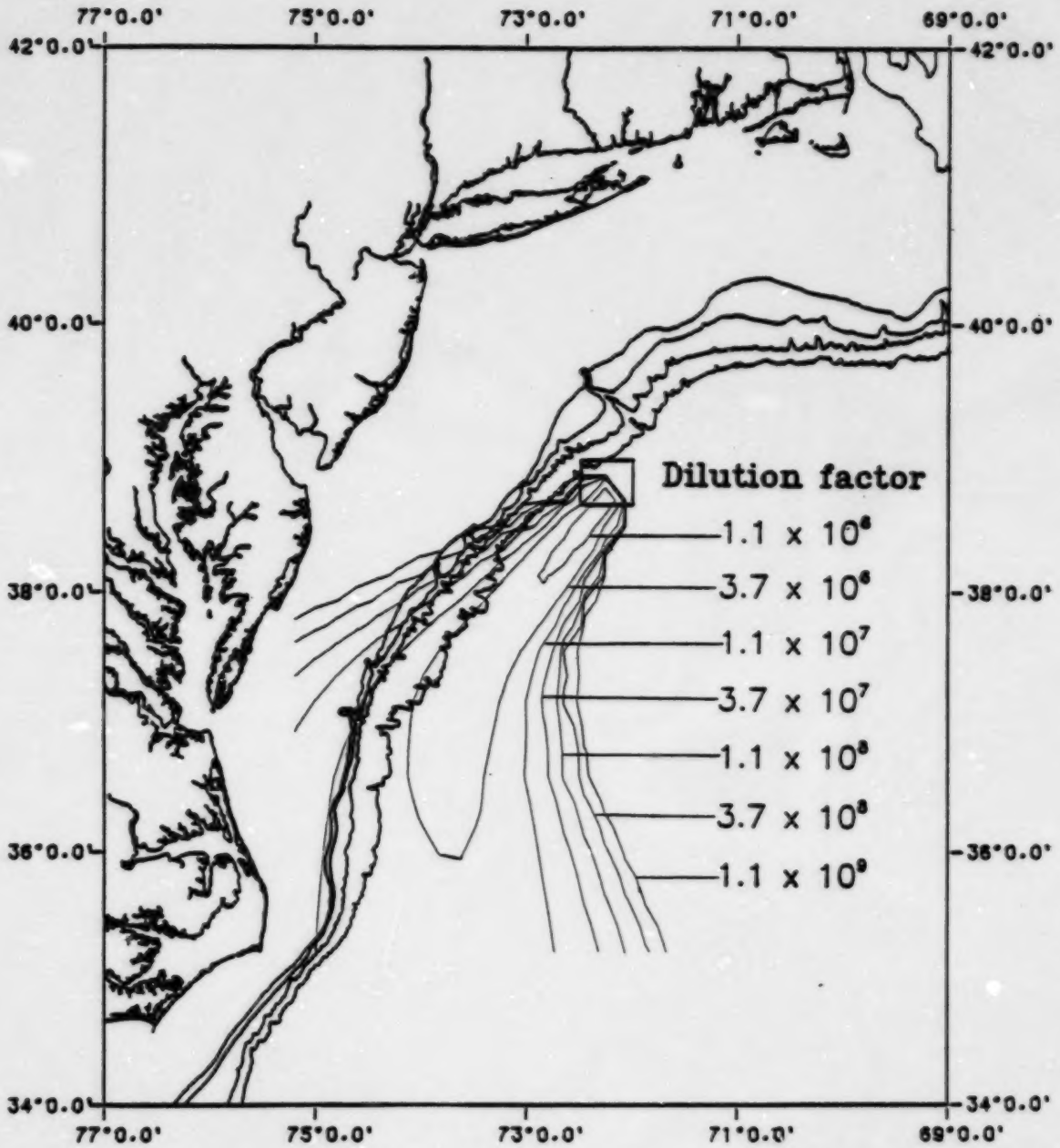
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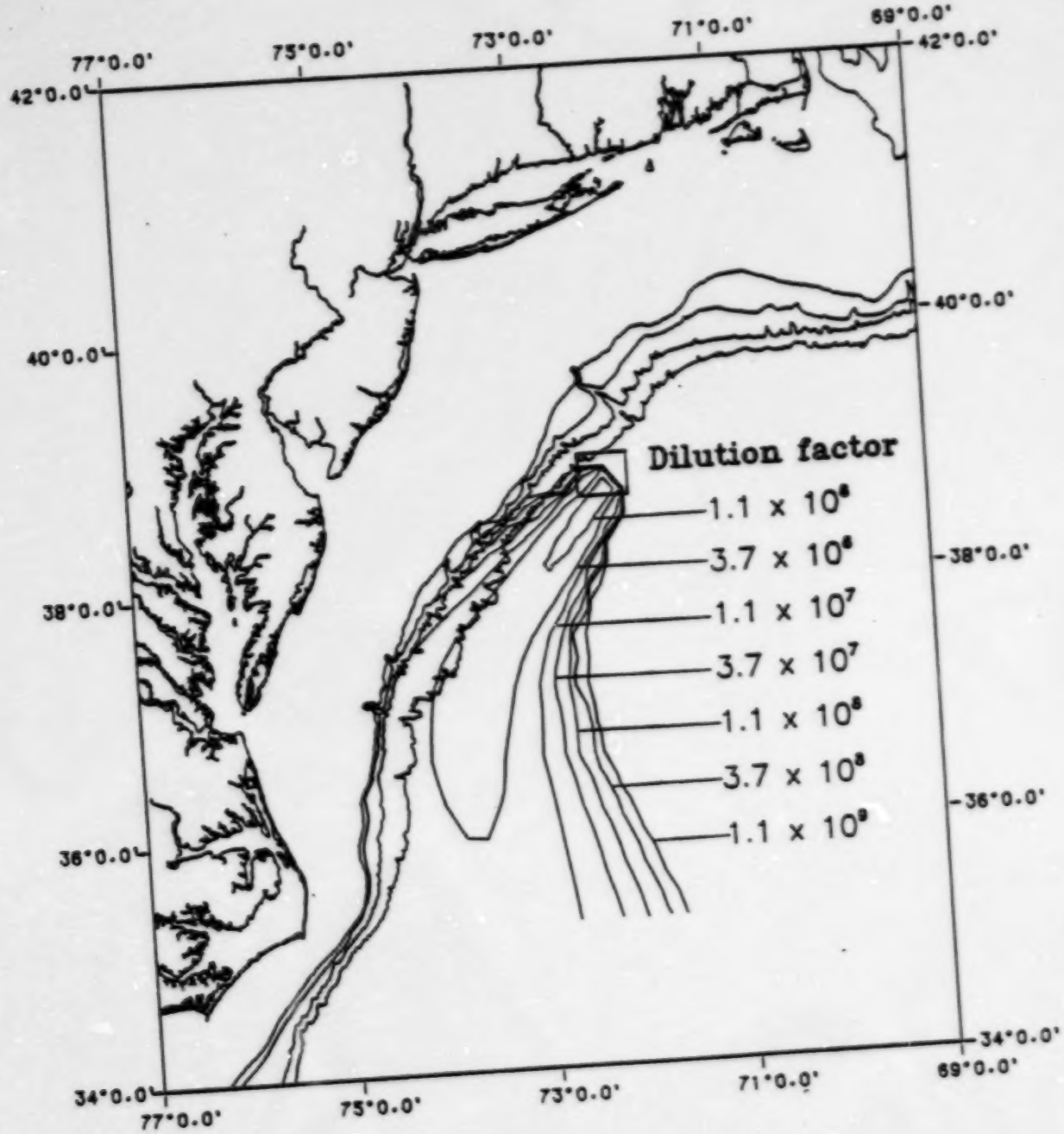
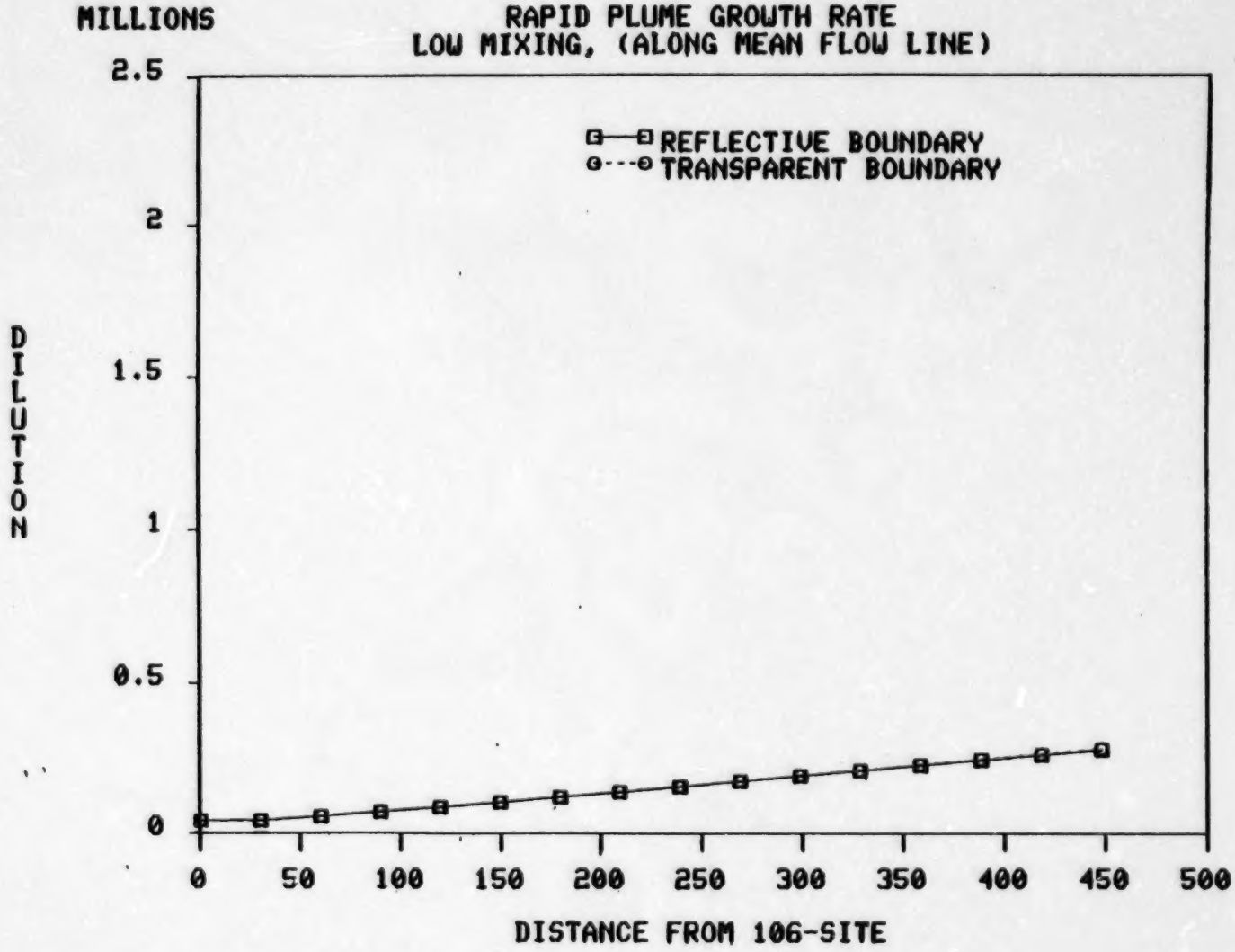
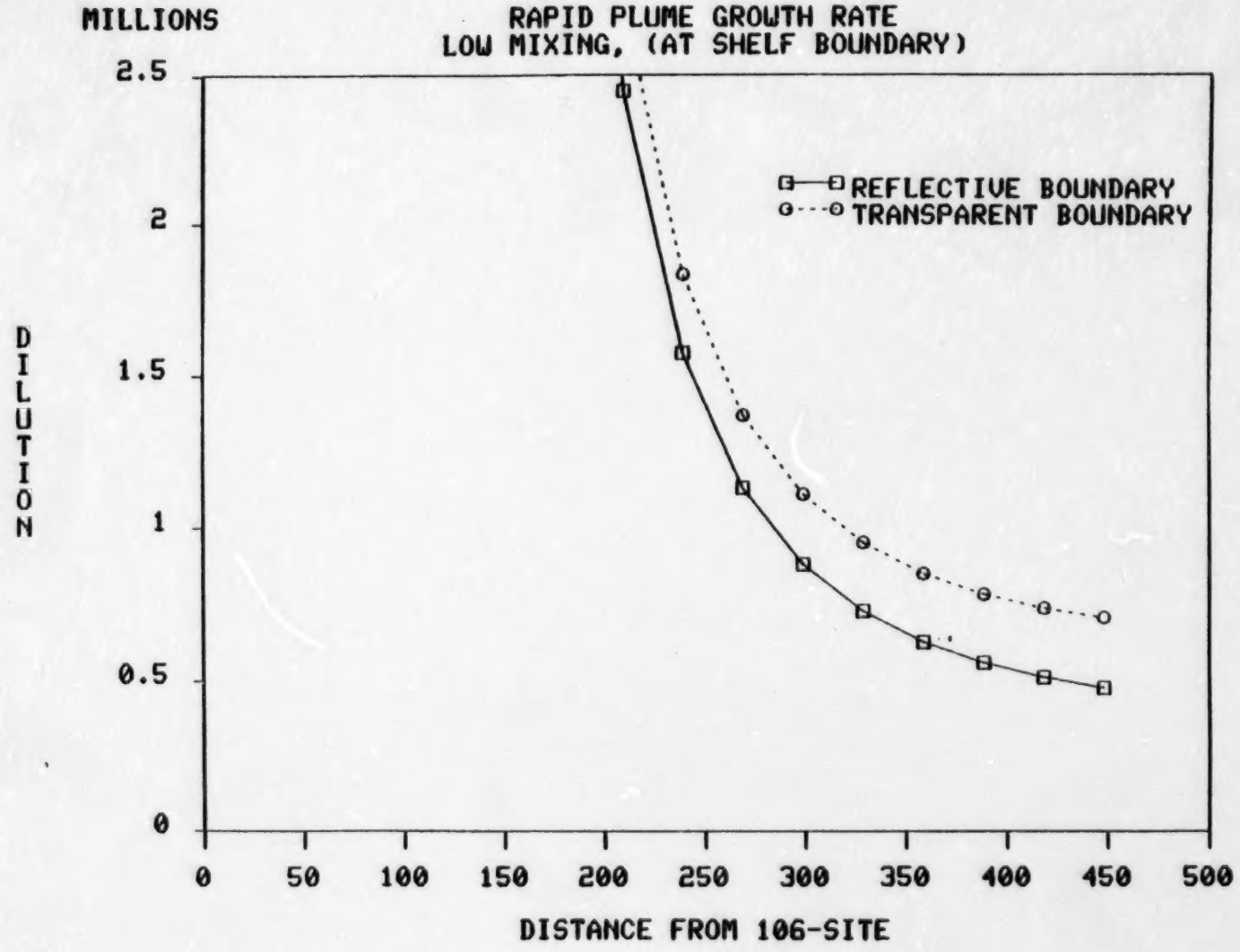
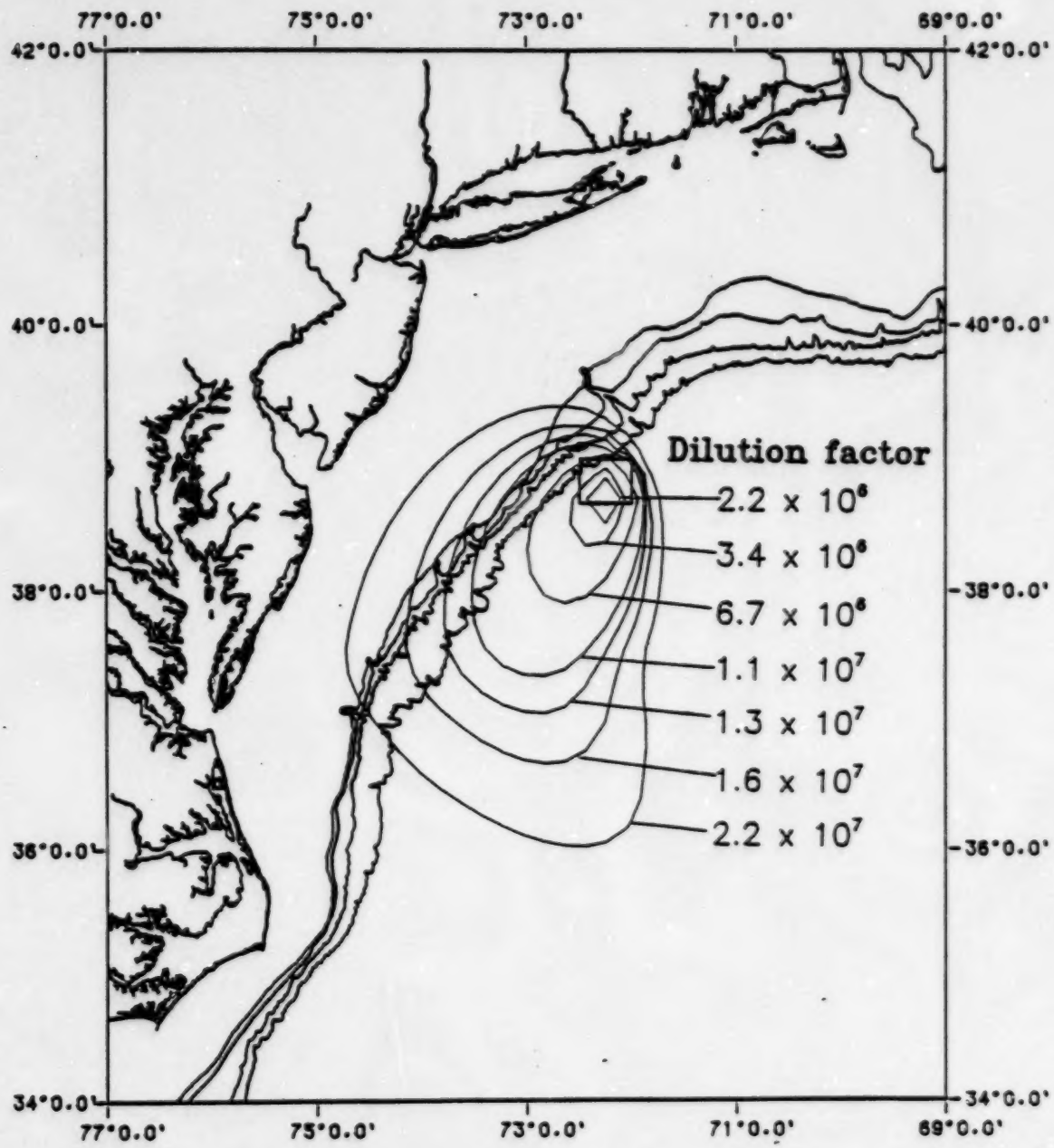
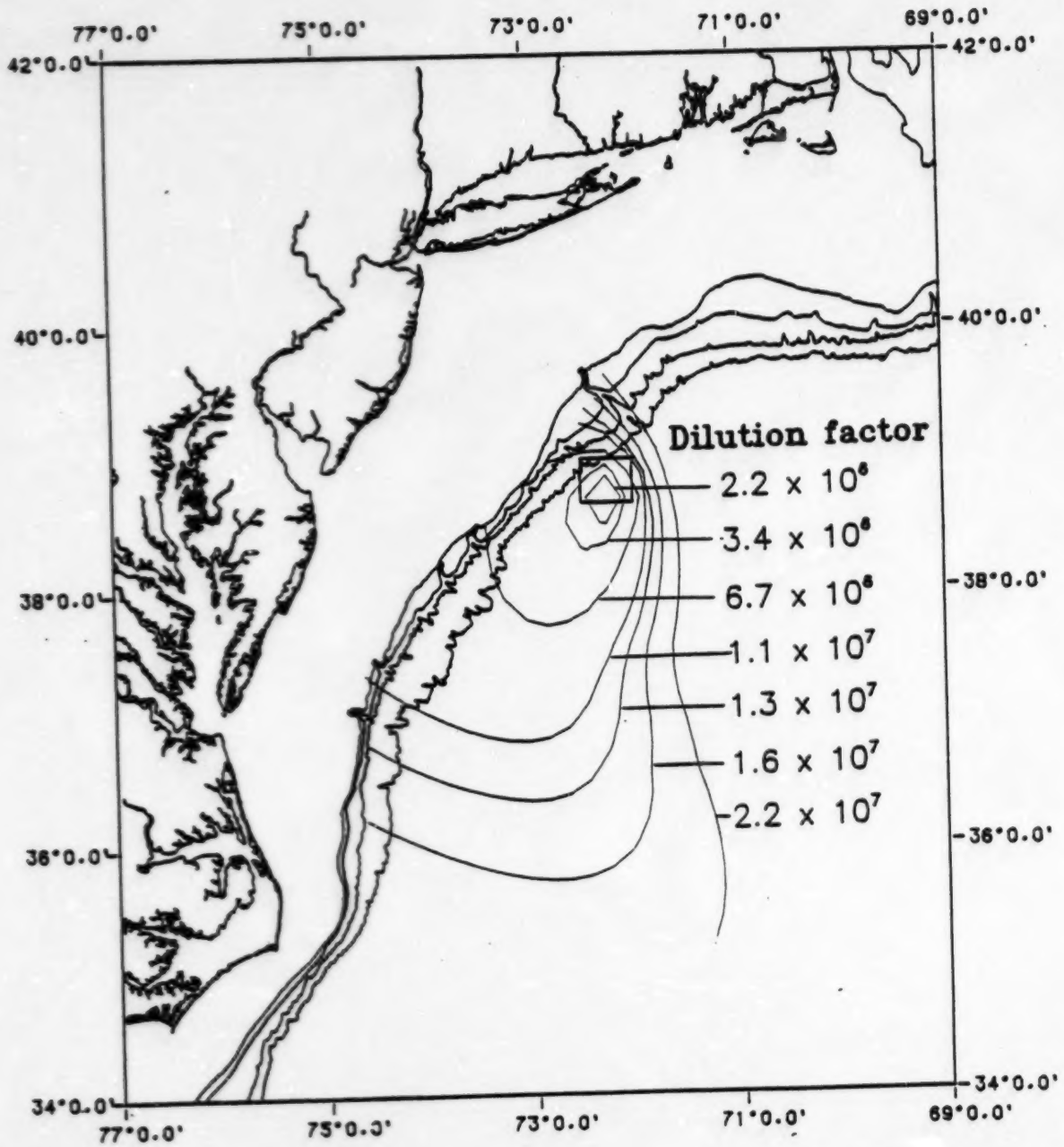
42°0.0'
40°0.0'
38°0.0'
36°0.0'
34°0.0'
Dilution factor
1.1 x 10⁶
3.7 x 10⁶
1.1 x 10⁷
3.7 x 10⁷
1.1 x 10⁸
3.7 x 10⁸
1.1 x 10⁹

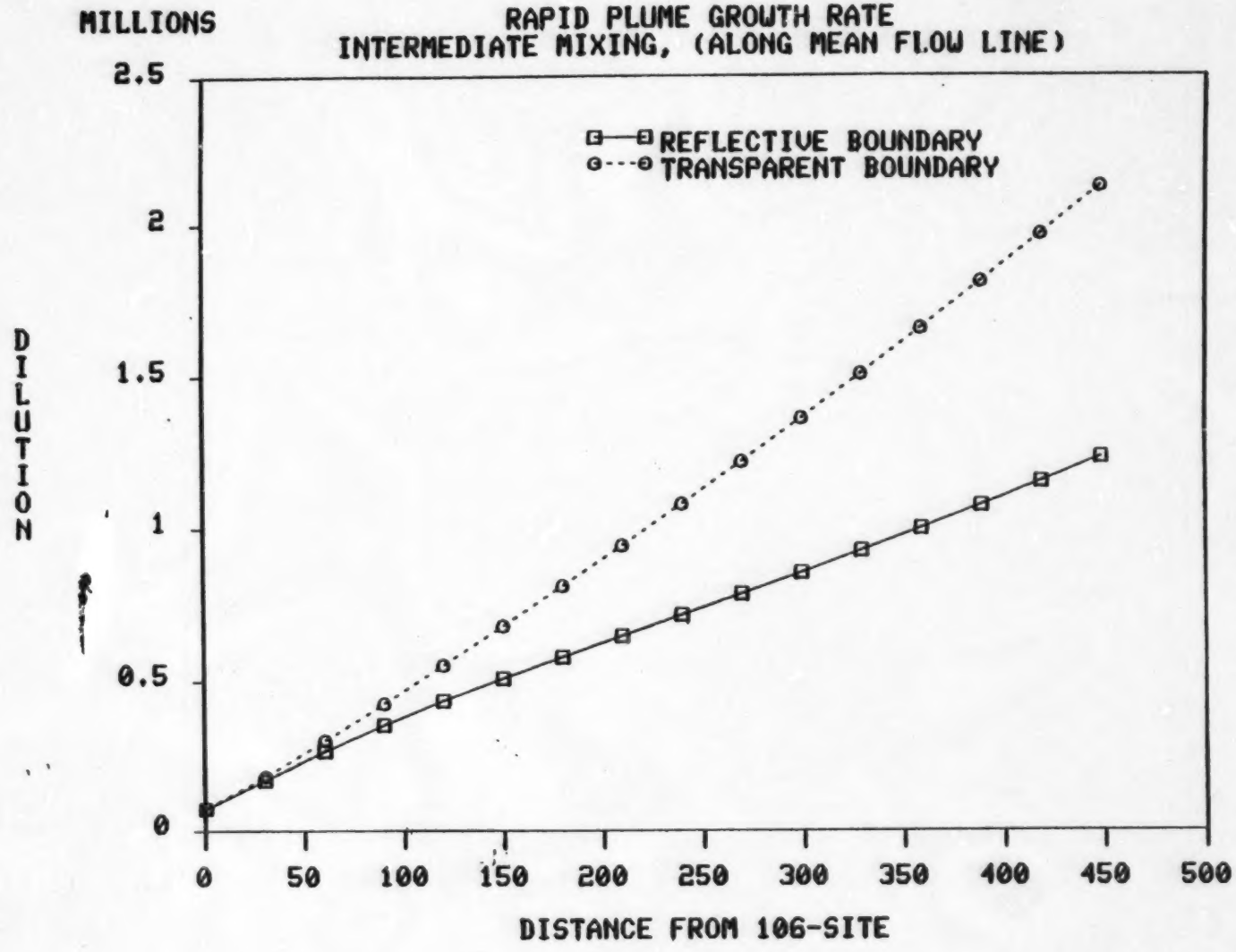

77°0.0'
75°0.0'
73°0.0'
71°0.0'
69°0.0'
42°0.0'
40°0.0'
38°0.0'
36°0.0'
34°0.0'
Dilution factor
1.1 x 10⁶
3.7 x 10⁶
1.1 x 10⁷
3.7 x 10⁷
1.1 x 10⁸
3.7 x 10⁸
1.1 x 10⁹

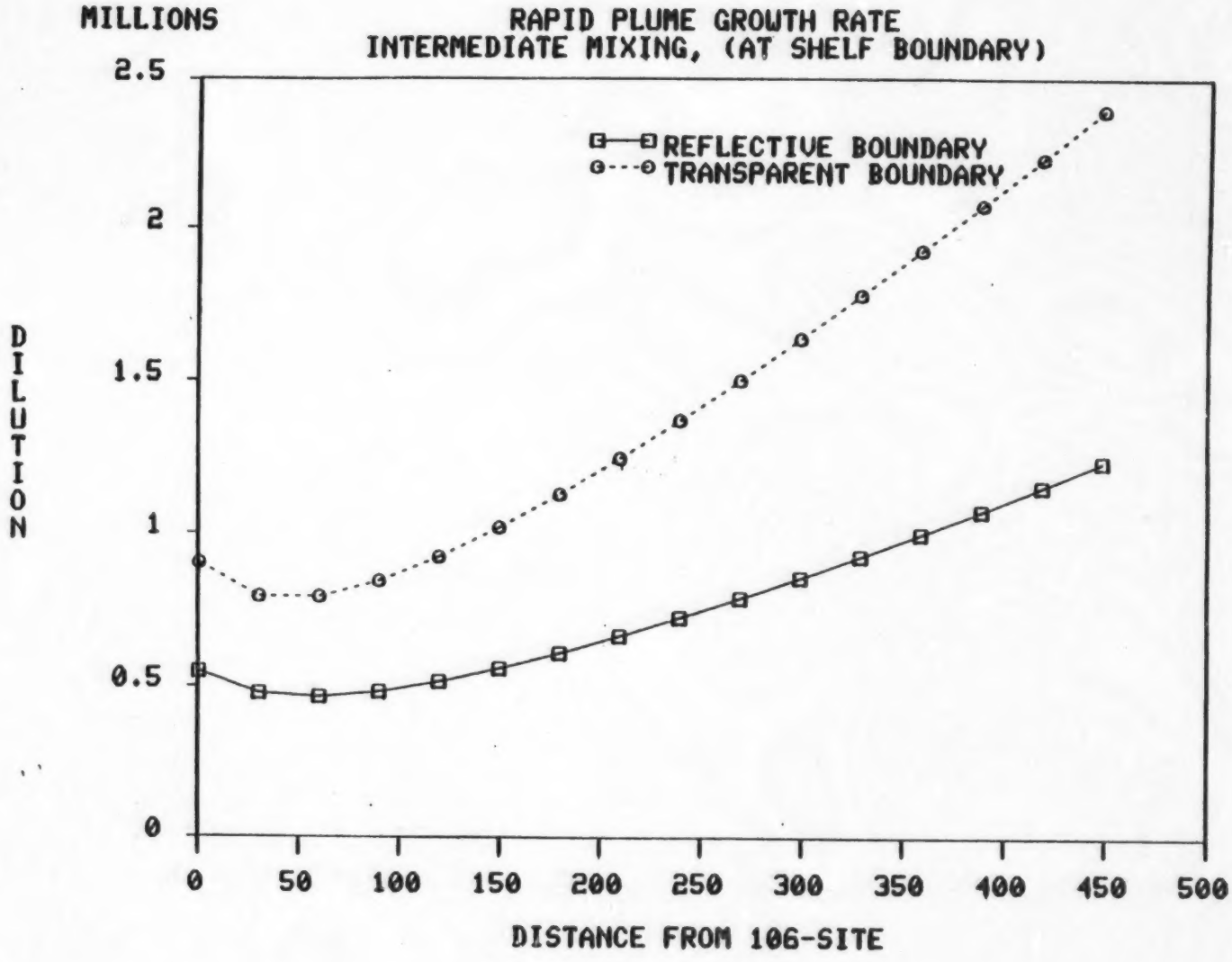

MILLIONS
RAPID PLUME GROWTH RATE
LOW MIXING, (ALONG MEAN FLOW LINE)
REFLECTIVE BOUNDARY
TRANSPARENT BOUNDARY
DILUTION
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300
350
400
450
500
DISTANCE FROM 106-SITE

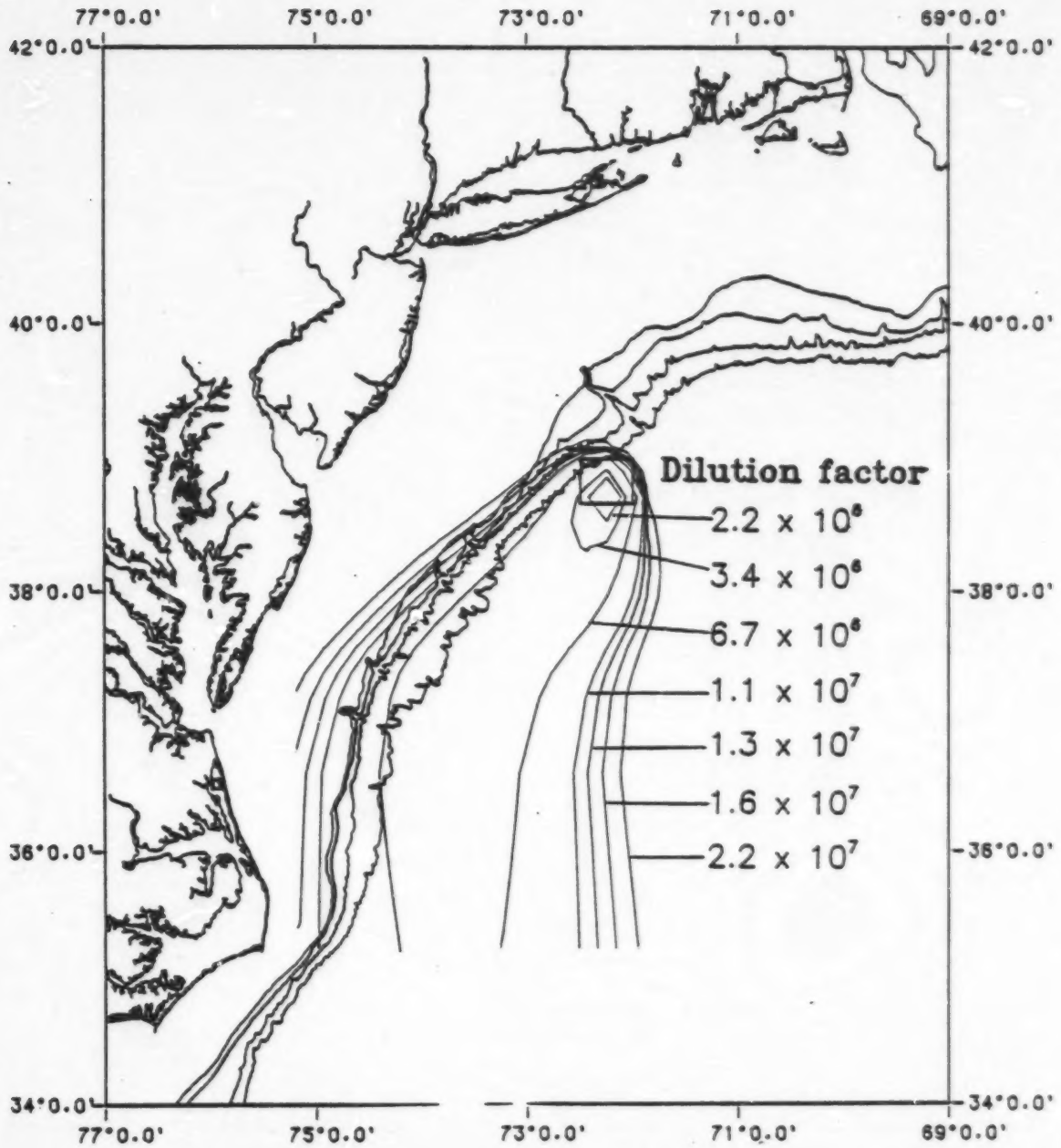

MILLIONS
RAPID PLUME GROWTH RATE
LOW MIXING, (AT SHELF BOUNDARY)
2.5
2
1.5
1
0.5
0
DILUTION
REFLECTIVE BOUNDARY
TRANSPARENT BOUNDARY
0
50
100
150
200
250
300
350
400
450
500
DISTANCE FROM 106-SITE

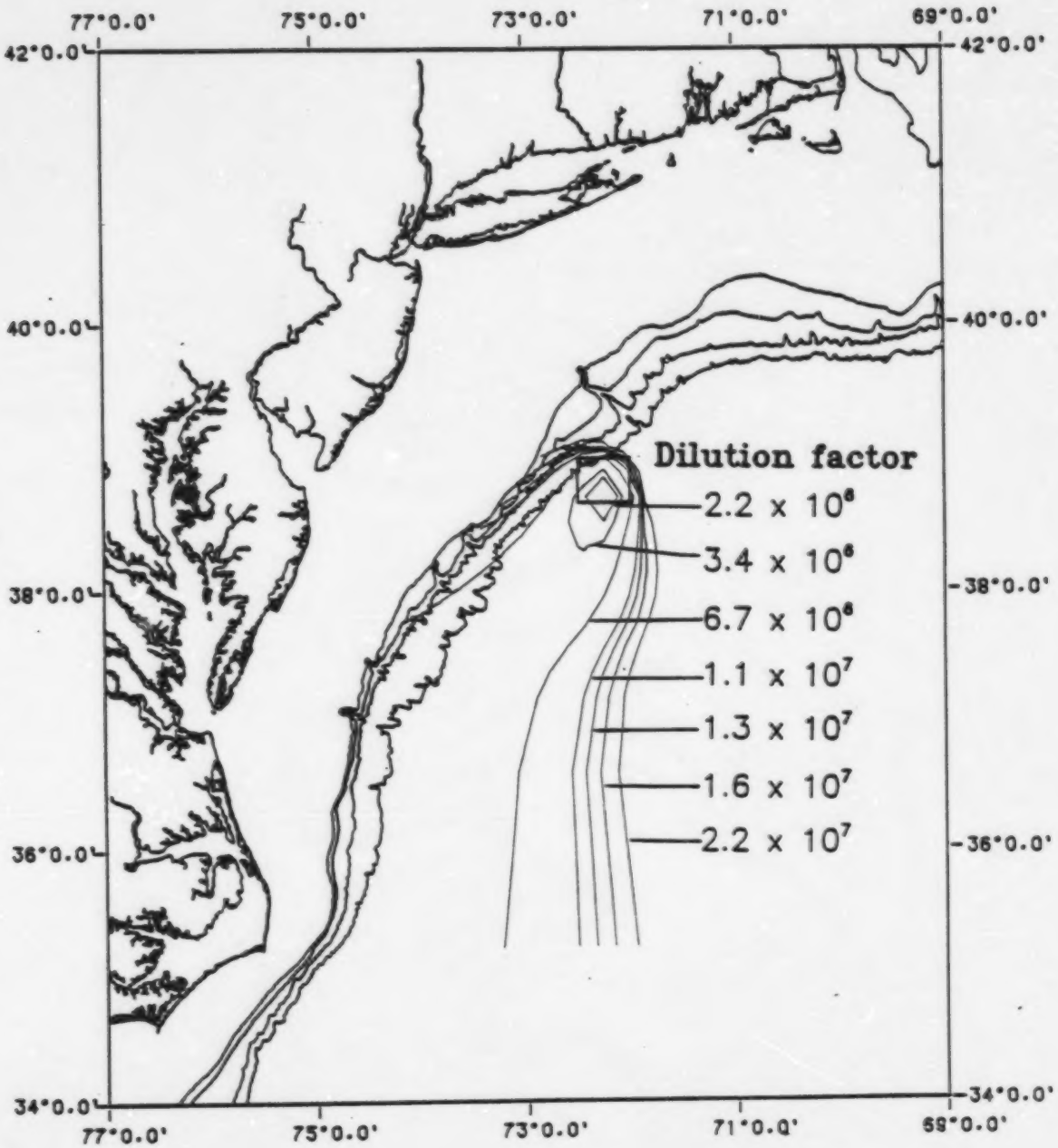

77°0.0'
75°0.0'
73°0.0'
71°0.0'
69°0.0'
42°0.0'
40°0.0'
38°0.0'
36°0.0'
34°0.0'
Dilution factor
2.2 x 10⁶
3.4 x 10⁶
6.7 x 10⁶
1.1 x 10⁷
1.3 x 10⁷
1.6 x 10⁷
2.2 x 10⁷

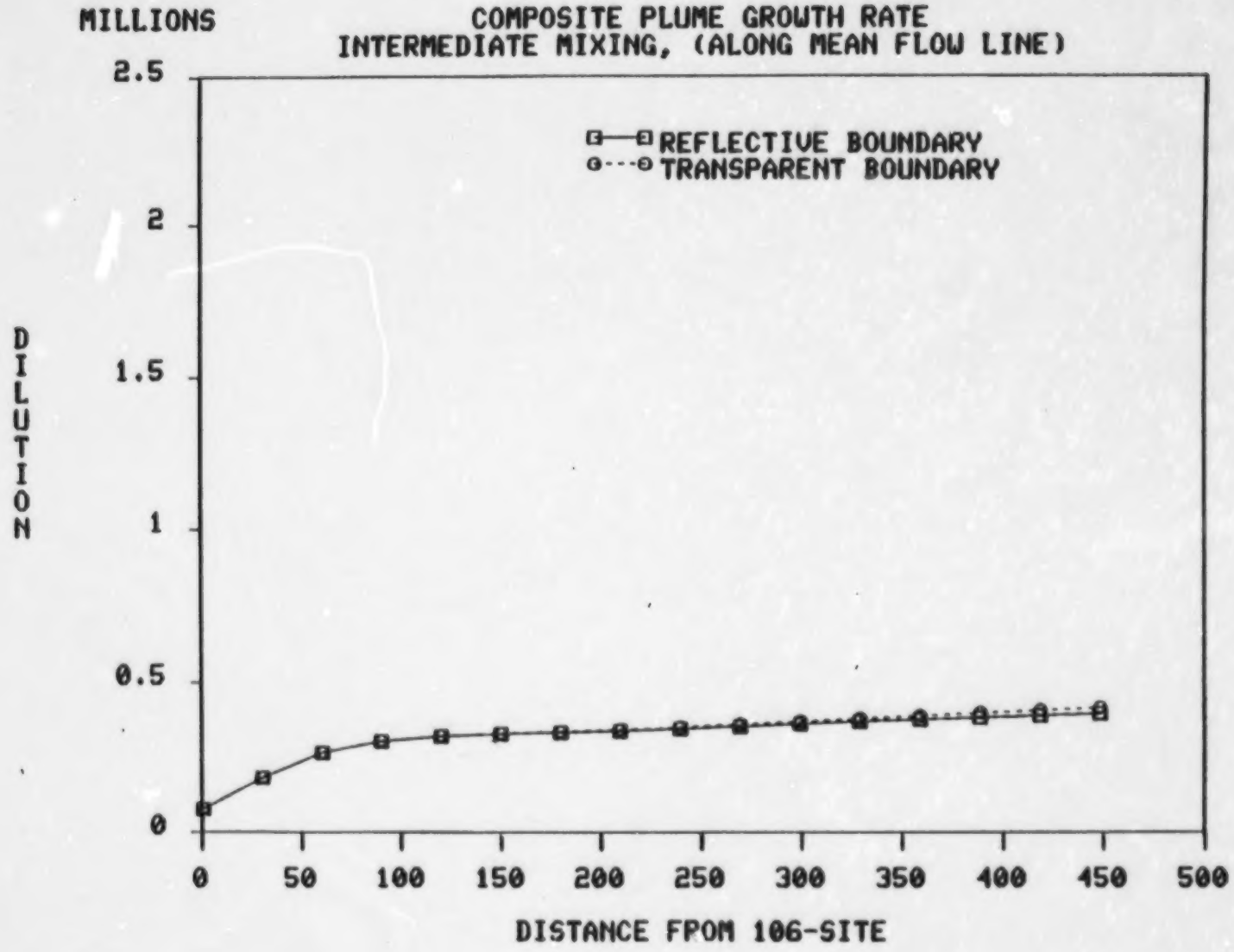

77°0.0'
75°0.0'
73°0.0'
71°0.0'
69°0.0'
42°0.0'
40°0.0'
38°0.0'
36°0.0'
34°0.0'
Dilution factor
2.2 x 10⁶
3.4 x 10⁶
6.7 x 10⁶
1.1 x 10⁷
1.3 x 10⁷
1.6 x 10⁷
2.2 x 10⁷

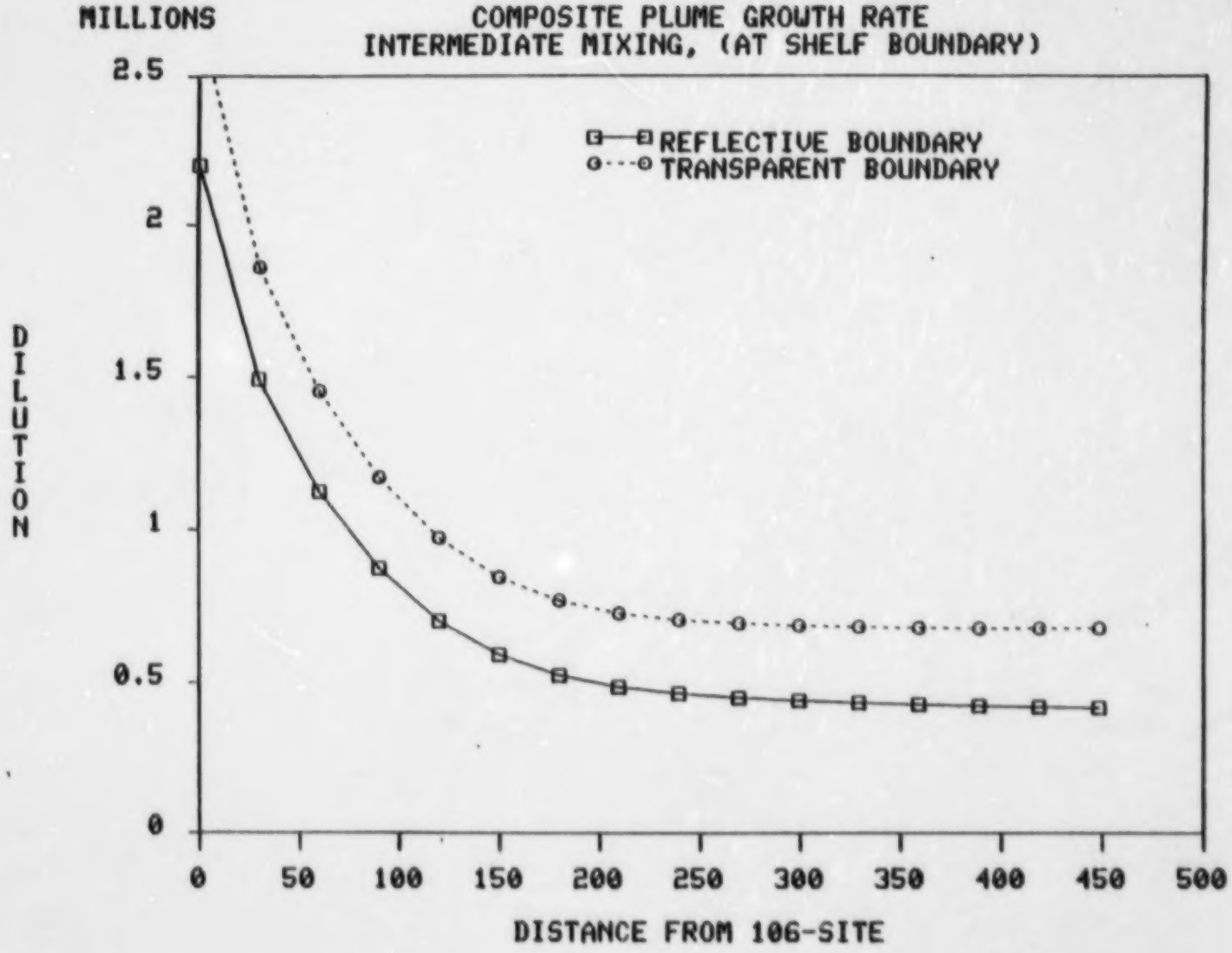

MILLIONS
RAPID PLUME GROWTH RATE
INTERMEDIATE MIXING, (ALONG MEAN FLOW LINE)
REFLECTIVE BOUNDARY
TRANSPARENT BOUNDARY
DILUTION
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300
350
400
450
500
DISTANCE FROM 106-SITE


MILLIONS
RAPID PLUME GROWTH RATE
INTERMEDIATE MIXING, (AT SHELF BOUNDARY)
REFLECTIVE BOUNDARY
TRANSPARENT BOUNDARY
DILUTION
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300
350
400
450
500
DISTANCE FROM 106-SITE


77°0.0'
75°0.0'
73°0.0'
71°0.0'
69°0.0'
42°0.0'
40°0.0'
38°0.0'
36°0.0'
34°0.0'
Dilution factor
2.2 x 10⁶
3.4 x 10⁶
6.7 x 10⁶
1.1 x 10⁷
1.3 x 10⁷
1.6 x 10⁷
2.2 x 10⁷


77°0.0'
75°0.0'
73°0.0'
71°0.0'
69°0.0'
42°0.0'
40°0.0'
38°0.0'
36°0.0'
34°0.0'
Dilution factor
2.2 x 10⁶
3.4 x 10⁶
6.7 x 10⁶
1.1 x 10⁷
1.3 x 10⁷
1.6 x 10⁷
2.2 x 10⁷


MILLIONS
COMPOSITE PLUME GROWTH RATE
INTERMEDIATE MIXING, (ALONG MEAN FLOW LINE)
REFLECTIVE BOUNDARY
TRANSPARENT BOUNDARY
DILUTION
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300
350
400
450
500
DISTANCE FROM 106-SITE


MILLIONS
COMPOSITE PLUME GROWTH RATE
INTERMEDIATE MIXING, (AT SHELF BOUNDARY)
REFLECTIVE BOUNDARY
TRANSPARENT BOUNDARY
DILUTION
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300
350
400
450
500
DISTANCE FROM 106-SITE